Argonne NATIONAL LABORATORY

Evaluation of CO_2 Capture and Sequestration Using Oxyfuels with AMIGA Economic Modeling

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U.S. DEPARTMENT OF ENERGY

ANNUAL REPORT 2010: Evaluation of CO_2 Capture and Sequestration Using Oxyfuels with AMIGA Economic Modeling

- Oxyfuel CO_2 recovery from pulverized-coal-fired power plants was extended across the existing fleet of domestic PC boilers linking process modeling (ASPEN) and assessing the economic impacts through a macroeconomic model (AMIGA—All-Modular Industry Growth Assessment.) The full energy cycle was considered, including mining, coal transportation, coal preparation, power generation, existing environmental regulations, facility water use, pipeline CO_2 conditioning, and pipeline transport of CO_2 to sequestration.
- **FY2010** $260K
- **Funding FY2008-2010** $780K
- **Contractor** Argonne National Laboratory
- **Contractor Project Manager** Dr. Mark C. Petri
- **Principal Investigator** Richard D. Doctor
- **Co-Principal Investigator** Dr. Donald A. Hanson
- **Project Management** Timothy Fout

Current Project: Evaluation of CO_2 Capture and Sequestration Using Oxyfuels with AMIGA Economic Modeling (FE49539 - Tim Fout)

- Use ASPEN to model Oxyfuels retrofit across the existing fleet of domestic PC boilers as a CO_2 Capture and Sequestration (CCS) strategy
- Cost-Engineering for Oxyfuels based on ASPEN
- Recognize that Oxyfuel investment may be a transitional strategy to Integrated Gasification Combined Cycle with CCS
- Link to an ongoing effort with the AMIGA (All-Modular Industry Growth Assessment) as the Computational General Equilibrium (CGE) macroeconomic, sector, & energy model
- Study the sectoral impacts of Oxyfuel CCS with AMIGA
- Limited consideration of site specific issues such as CO_2 transport and water availability

Oxyfuels process modeling will accelerate deployment

1. ***PC Boiler Gas-side*** – Oxyfuels compared to Amines —***What are the benefits?***
   – Oxyfuels avoids SCR, lowering costs.
2. ***Oxygen delivery*** — ***What is the optimal O_2 purity for Oxyfuels?***
   – Higher purity O_2 is important in managing N_2 and Argon. However, too high a purity of O_2 leads to dis-proportionation. This is an economic trade-off.
3. ***Steam-cycle*** — ***What will be the impact on steam cycles?***
   – Rebalancing the steam cycle and turbines will be necessary for CCS using Amines
4. ***Flue Gas Desulfurization*** — ***What is CO_2 leakage with sulfur control?***
   – There is a clear advantage to supplying higher purity O_2 from ASU. CO_2 leakage justifies O_2 use for Forced Oxidation
   – Moisture from FGD increases costs of downstream CO_2 conditioning
5. ***CO_2 conditioning*** – ***What will CO_2 conditioning cost?***
   – 2 cold boxes are not sufficient for meeting some reservoir specifications and an EOR CO_2 tower was added
   – Dilution of CO_2 by non-condensable gases Argon, O_2 and N_2 lowers the temperature required for liquefaction

Process design supplies essential intermediate stream details addressing important process issues

Energy System Simulations Instill Investor Confidence in Undertaking Oxyfuel Retrofits.

Our simulations highlight four scenario cases as listed below:

1. ***Attractive Private Investment***. Electric utilities naturally like to life extend their existing power plants while addressing CO_2 emissions.
   - ***How will parasitic load and derating be mitigated through system-wide adjustments?***
2. ***Perceived GHG urgency*.** Actions that can be accomplished in the near- to medium-term may be favored in today's policy environment.
   - ***Might near-term retrofits be mandated?***
   - ***How will experience with retrofits accelerate other generating technologies with CCS?***
   - ***How will Oxyfuel retrofits play under economy-wide GHG reduction targets in 2050?***
   - ***What are resulting economy-wide CO_2 emissions?***

Energy System Simulations Instill Investor Confidence in Undertaking Oxyfuel Retrofits.

Scenario cases (Continued)

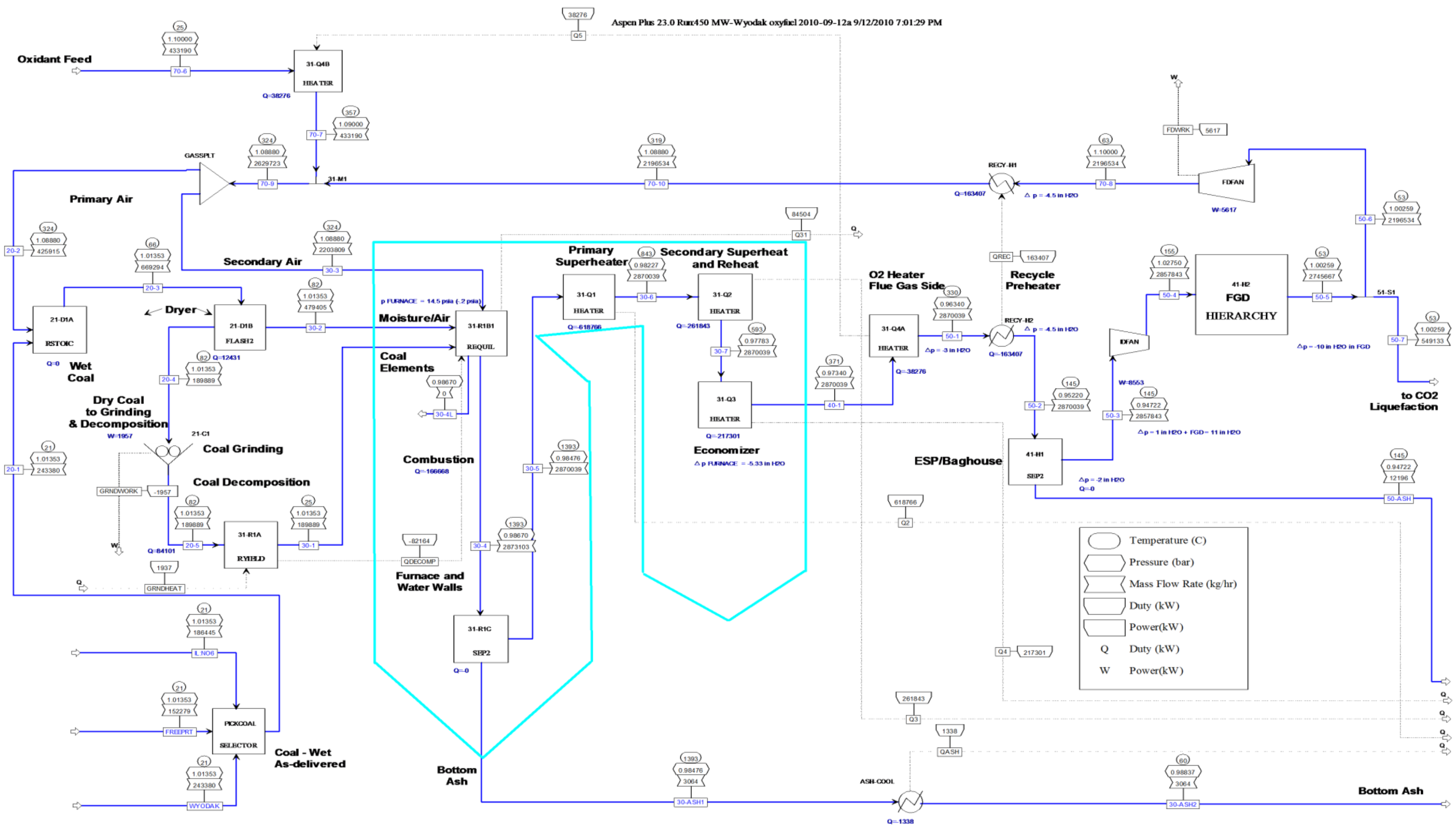
3. Transportation Electrification. Demand for generation technologies will increase.

- ***What will comprise the expanded generation fleet to accommodate plug-in vehicles, new electric regional transit, and continued growth in innovative electric devices?***

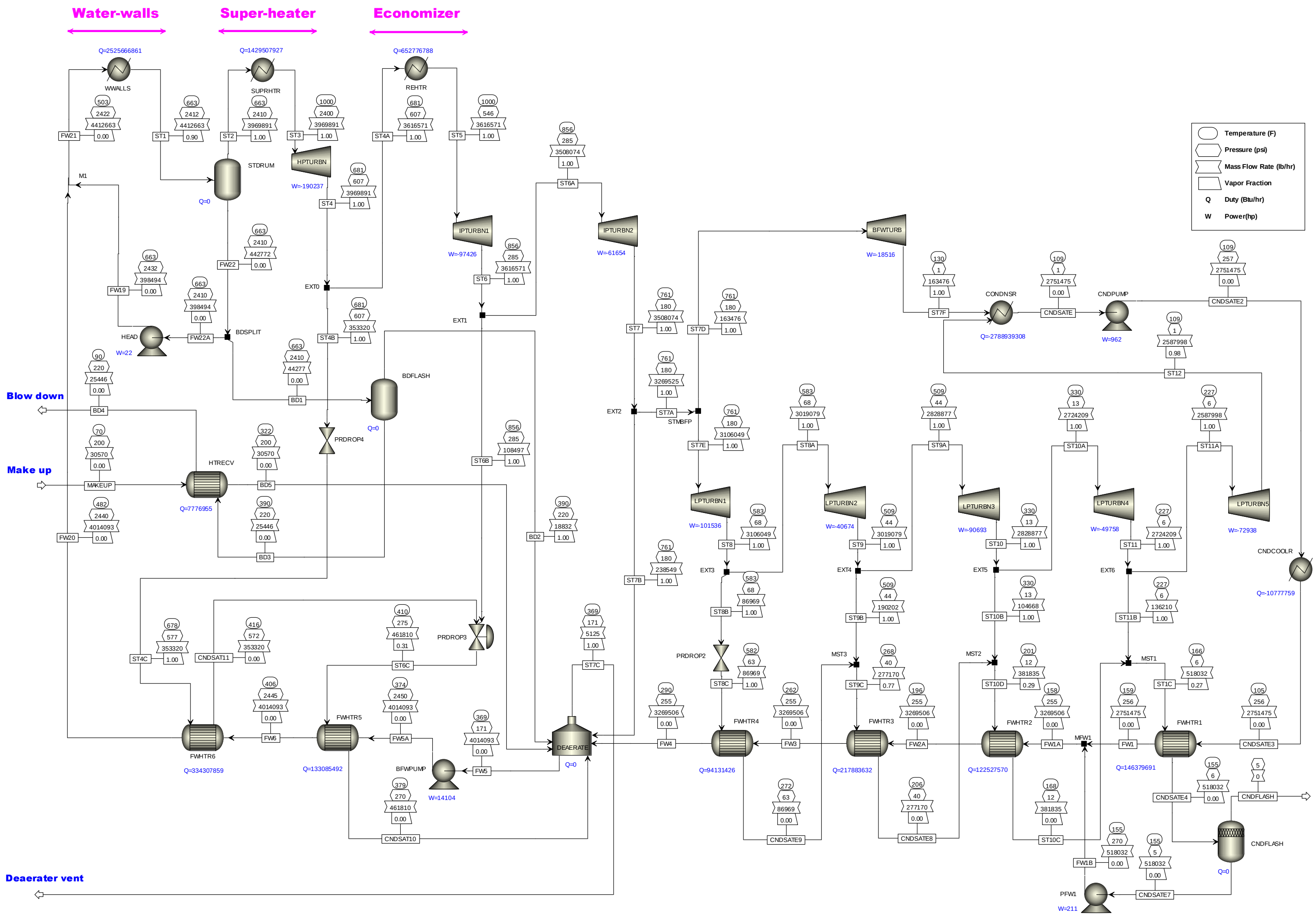
4. Energy Security Needs. Domestic coal use with CCS fosters energy security.

- ***Will global transition economies continue with rapid growth?***
- ***Will co-production plants be needed to supplement petroleum, particularly diesel fuel?***

Air and Oxyfuel systems were run at 150, 300 and 450 MW with 3 standard coals - These are being explored with variations in O_2 95-99.5%



ASPEN: Oxyfuels - Steam-side simulation
Critical to comparing Amine retrofits to Oxyfuels



FGD with electrolytes: 450 MW Oxyfuel IL#6 coal

Reaction	Type	Stoichiometry
1	Equilibrium	2 H2O <--> H3O+ + OH-
2	Equilibrium	CO2 + 2 H2O <--> H3O+ + HCO3-
3	Equilibrium	HCO3- + H2O <--> H3O+ + CO3--
4	Equilibrium	SO2 + 2 H2O <--> H3O+ + HSO3-
5	Equilibrium	HSO3- + H2O <--> H3O+ + SO3--
6	Equilibrium	CAOH+ <--> CA++ + OH-
CASO3(S)	Salt	CASO3(S) <--> CA++ + SO3--
CASO3*HM	Salt	CASO3*HM <--> CA++ + SO3-- + 0.5 H2O
CA(OH)2	Salt	CA(OH)2 <--> CAOH+ + OH-
CACO3(S)	Salt	CACO3(S) <--> CA++ + CO3--

1,919.7 k tonne/h CO_2

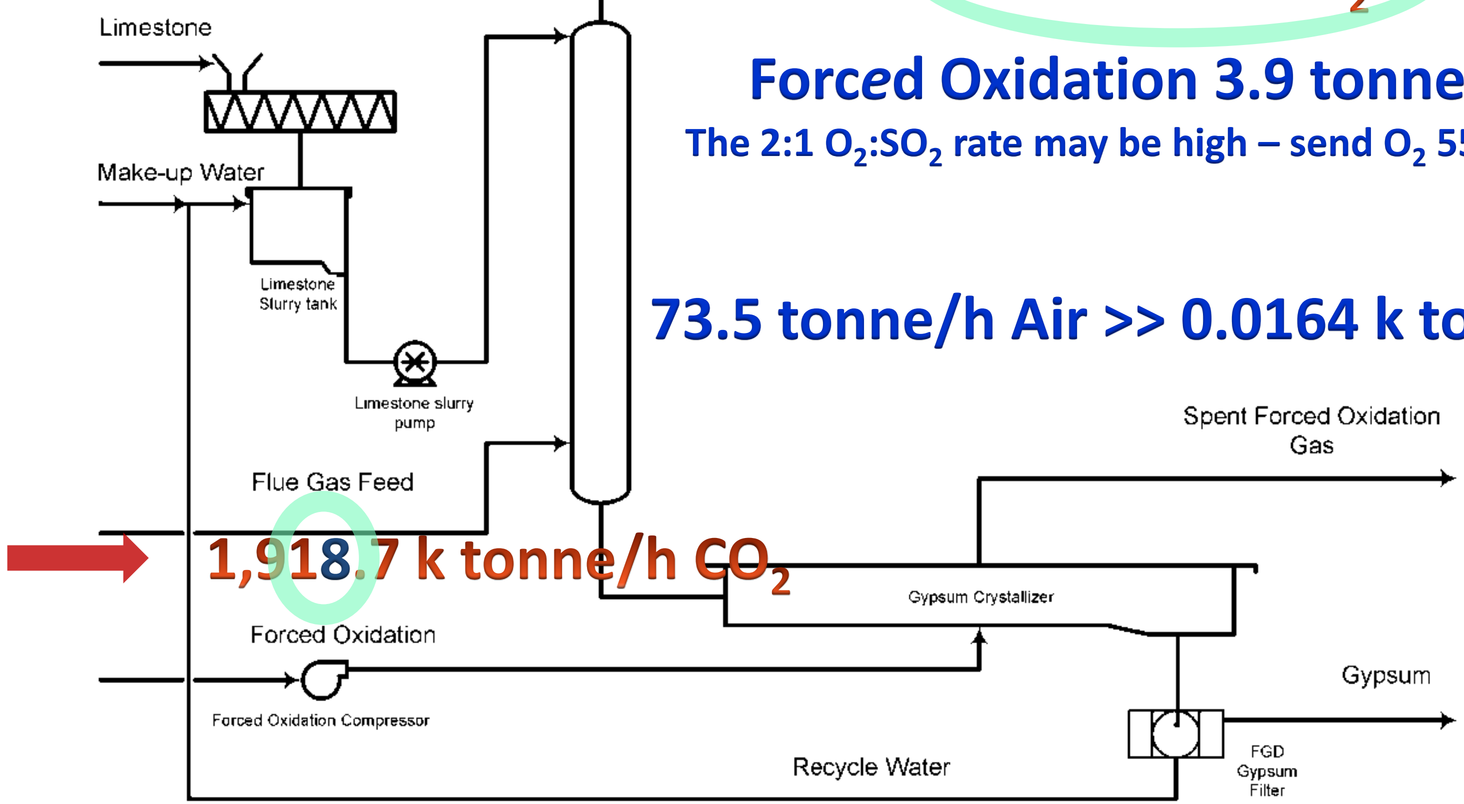
FGD emits CO_2

Forced Oxidation 3.9 tonne/h O_2

The 2:1 O_2:SO_2 rate may be high – send O_2 55% to boiler

73.5 tonne/h Air >> 0.0164 k tonne/h CO_2

1,918.7 k tonne/h CO_2



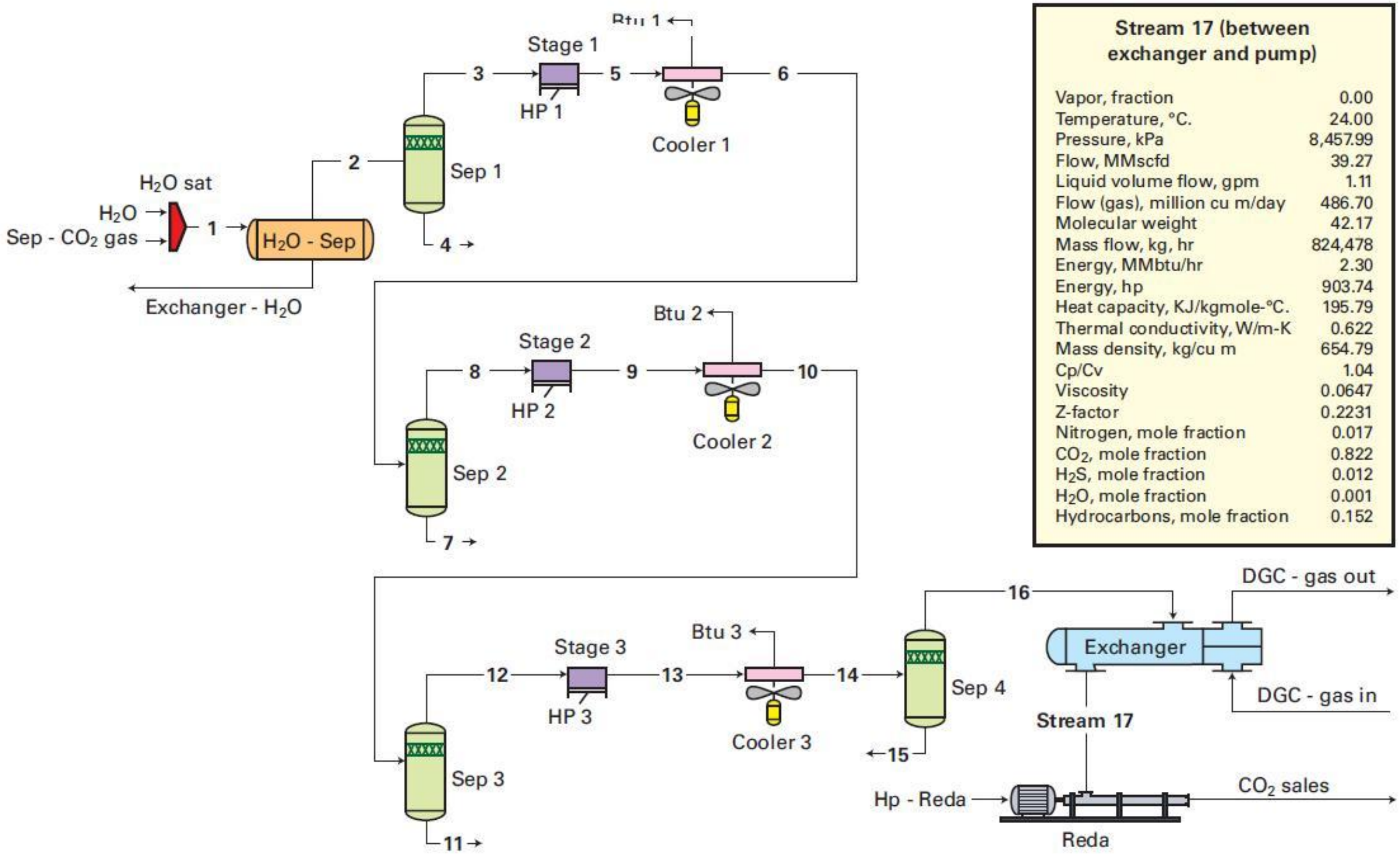
FGD Design Conditions for 99.5% SO_2 removal

- L/G — 85 -115 gal/1000 acfm
- Forced Oxidation — O_2/SO_2 – 2:1
- Forced Oxidation air to Crystallizer from Cryogenic ASU O_2 (99.6% purity) to avoid N_2 and Argon infiltration
- Thickener underflow — 35% solids (and operating temperature)
- Gypsum — Sulfate:Sulfite (10:1) also occluded water

- ***For 450 MW Oxyfuel – Illinois #6 coal***
  - Oxygen use = 3.9 tonne/hr
  - CO_2 "slip" with Air Forced Oxidizer off-gas= 16 tonnes/hr
  - Argon in CO_2 exit gas goes up by 10%
  - CO_2 leakage justifies O_2 use for Forced Oxidation
  - Dilution of CO_2 by non-condensable gases Argon, O_2 and N_2 lowers the temperature required for liquefaction to levels that may not be achievable with evaporative cooling towers alone.
  - The concentration of non-condensable gases may violate safe operating specifications for the pipeline.

Weyburn CO_2 delivery operates under reducing conditions with H_2S (not SO_2 as in Oxyfuels) it is O_2 free

Kenneth Vargos, *Restaged CO_2 compressors, new pumps remove bottleneck at Weyburn*,
Oil & Gas Journal November 16, 2009 Vol. 107 Issue 43 (Note: the high Hydrocarbons are C_1-C_3)



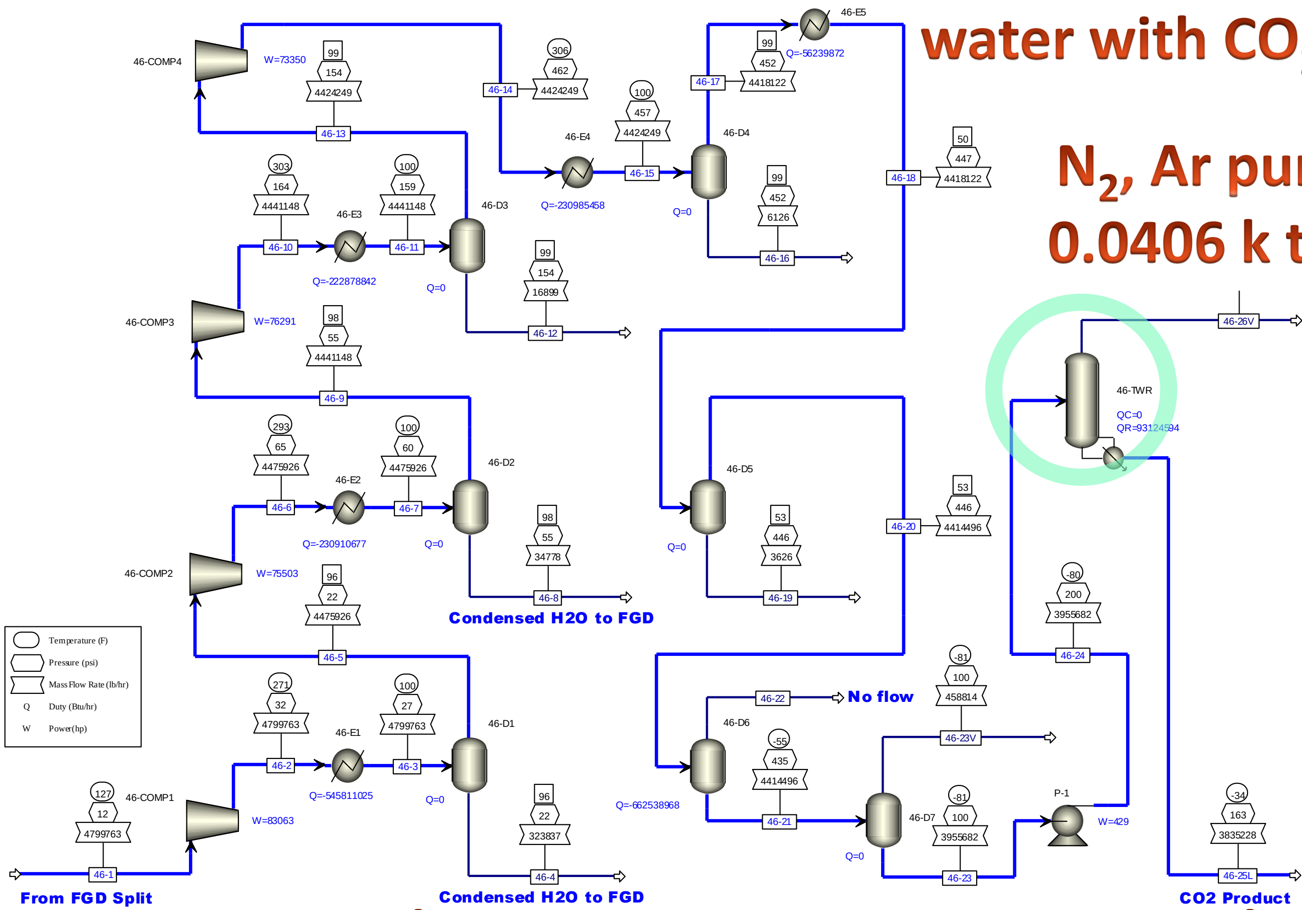
Stream 17 (between exchanger and pump)

Vapor, fraction	0.00
Temperature, °C.	24.00
Pressure, kPa	8,457.99
Flow, MMscfd	39.27
Liquid volume flow, gpm	1.11
Flow (gas), million cu m/day	486.70
Molecular weight	42.17
Mass flow, kg, hr	824,478
Energy, MMbtu/hr	2.30
Energy, hp	903.74
Heat capacity, KJ/kgmole-°C.	195.79
Thermal conductivity, W/m-K	0.622
Mass density, kg/cu m	654.79
Cp/Cv	1.04
Viscosity	0.0647
Z-factor	0.2231
Nitrogen, mole fraction	0.017
CO_2, mole fraction	0.822
H_2S, mole fraction	0.012
H_2O, mole fraction	0.001
Hydrocarbons, mole fraction	0.152

CO_2 Delivery and Recirculation using 4 cold boxes *followed by an EOR CO_2 tower* *(10 ppm O_2 case)*

FGD is a convenient sink for knock-out water with CO_2

N_2, Ar purge; 67% CO_2
0.0406 k tonnes/h CO_2



1,918 k tonnes/h CO_2

1,779 k tonnes/h CO_2

Process Design - Conclusions

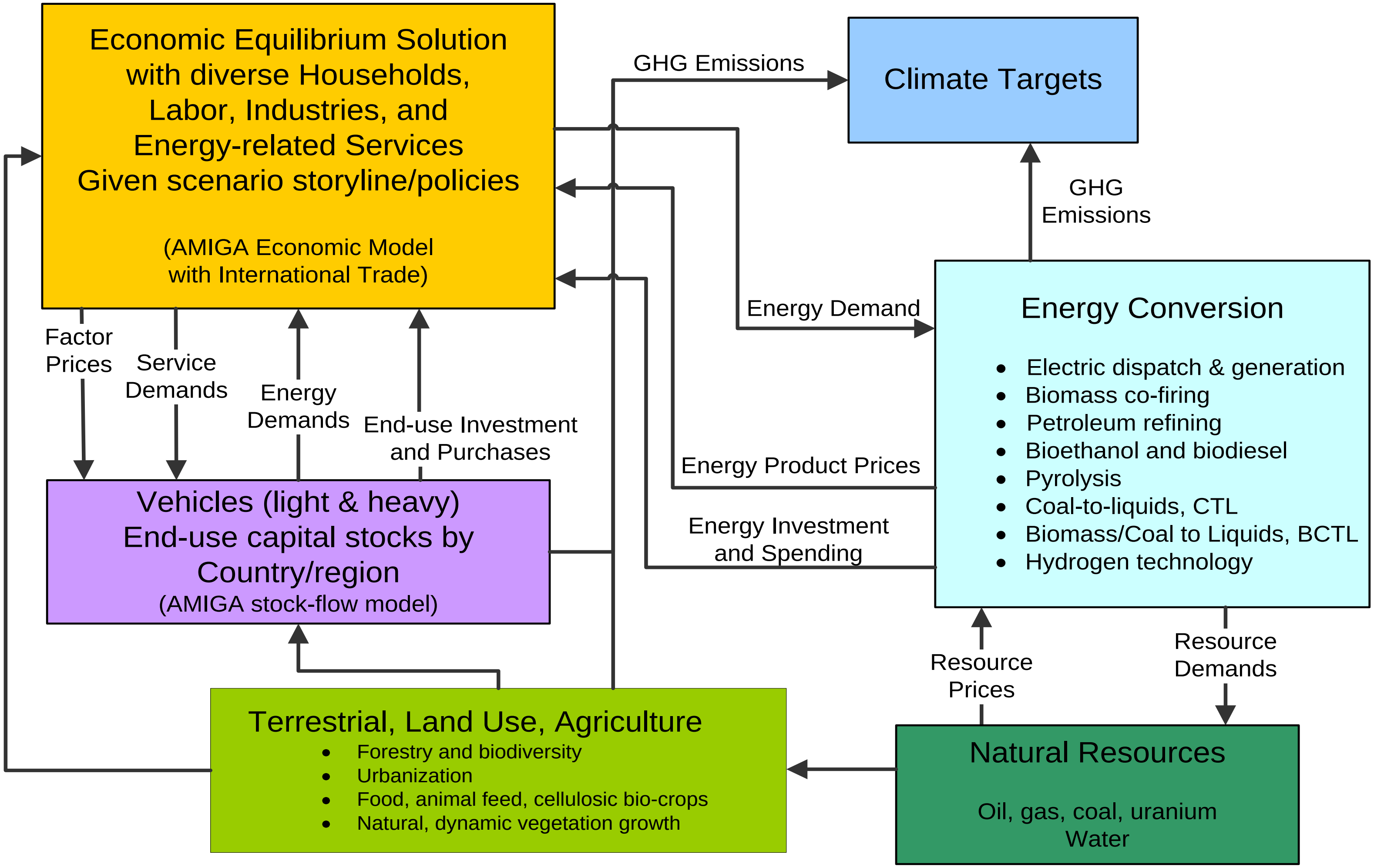
- *Process design supplies essential intermediate stream details addressing important process issues*

- *Oxyfuels process modeling will accelerate deployment*

Managing Your Existing Plant Asset: Considerations

- When is the best time to retrofit your unique plant?
  - Retrofit costs may decrease with R&D results; performance may increase
  - Experience/learning will increase over time
  - Price of a CO_2 allowance (carbon charge) will likely increase
  - Plant may be in need of refurbishment
- Positive tradeoffs
  - Less expenditures on carbon allowances
  - More efficient due to attendant refurbishment/life-extension investments
  - Higher Capacity Factor due to lower total variable costs (i.e., higher dispatch)
- Negative tradeoffs
  - Loss of electricity sales due to capacity derating after retrofit
  - Retrofit/refurbishment capital outlays (but less than a new advanced coal plant)

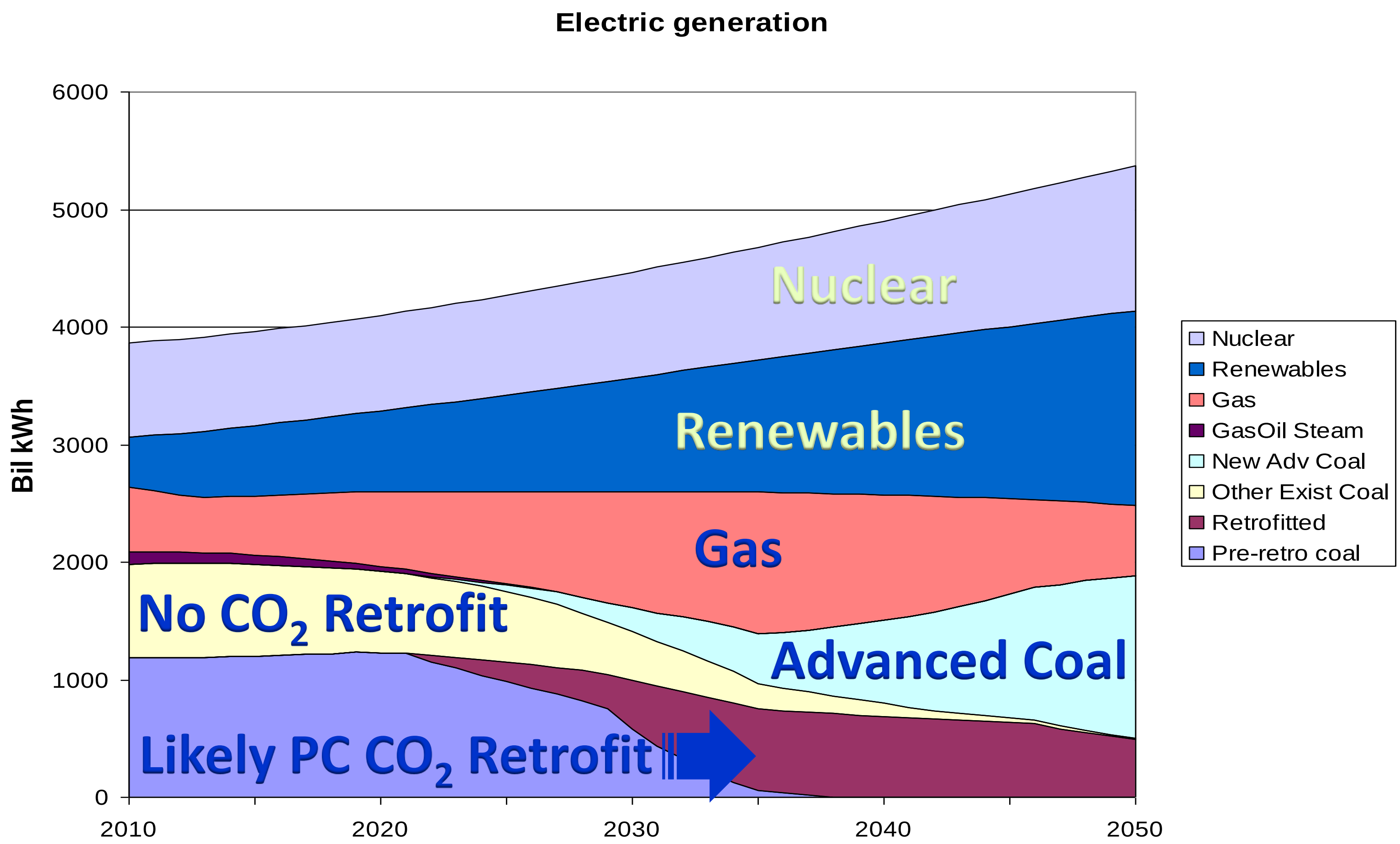
Overview of the AMIGA Model General Equilibrium System including the Utility Planning and Compliance Model and Unit Inventory



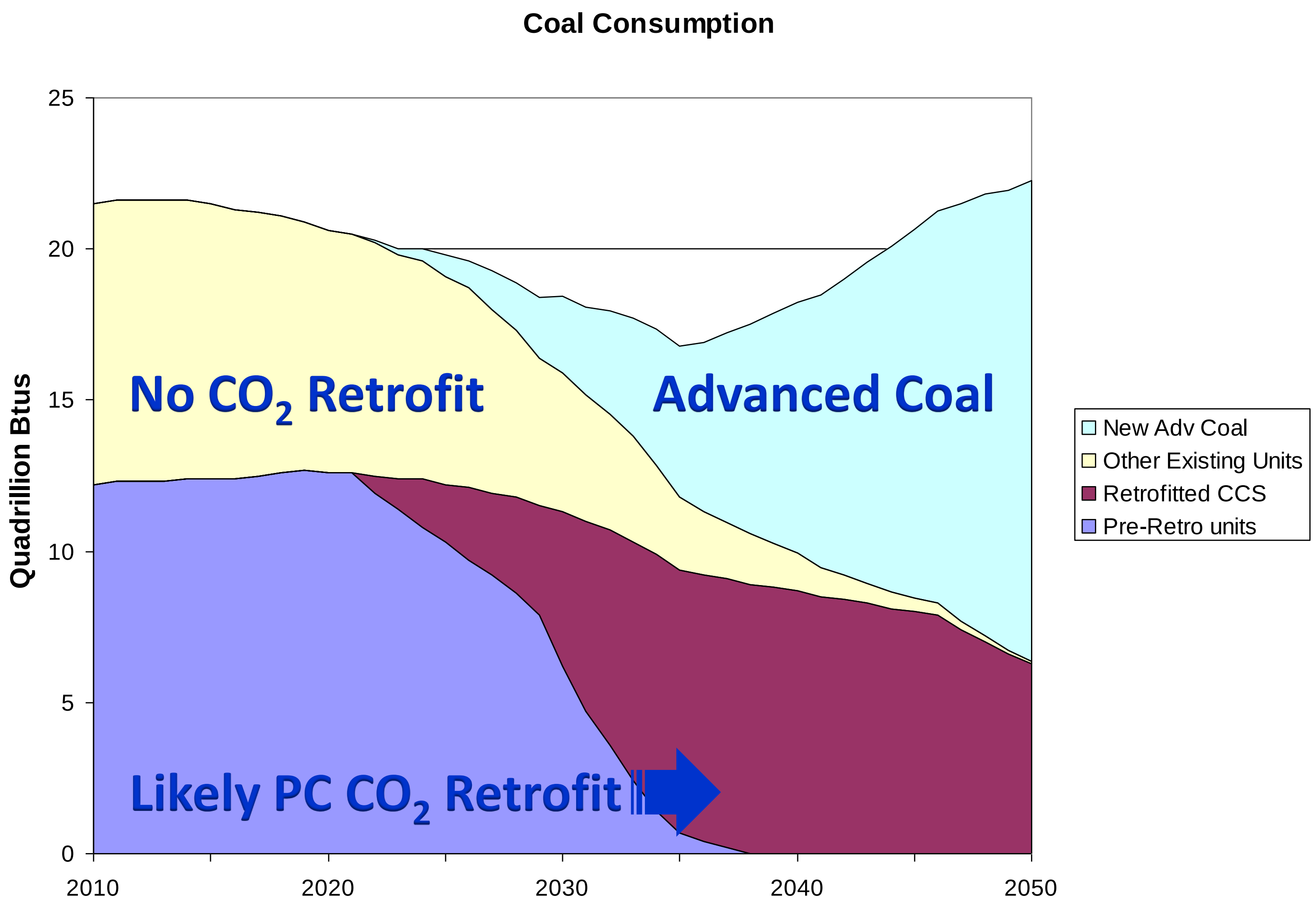
Analysis of Carbon Reduction Policy Scenarios

- In this scenario, electricity demand is growing at an average of 0.89% per year:
  - Increased electrification from plug-in HEVs
  - Increased electrification from continued growth in electrical/electronic equipment
  - Balanced by greater energy efficiency efforts
- Increased gas production from the Marcellus and other gas shales, under a carbon policy, is diverted from power generation to industrial/commercial CHP, and transportation uses (CNG LDV fleets, LNG heavy truck fleets)
- Based on our Stanford University Energy Modeling Forum simulations we use a price path for CO2 which grows at 2% per year (about the rate of economic growth), but with an initial 5-year phase-in period
- The CO_2 price path shifts up if the overall CO_2 reduction target needs to be tighter
- In the following run:
  - 368 existing PC units (150 GW) are retrofitted with CCS over the period 2022 to 2038
  - These tend to be the newer, larger, more efficient units
  - The average size is 410 MW
  - NETL and partners meet capture performance and cost goals for existing and new units

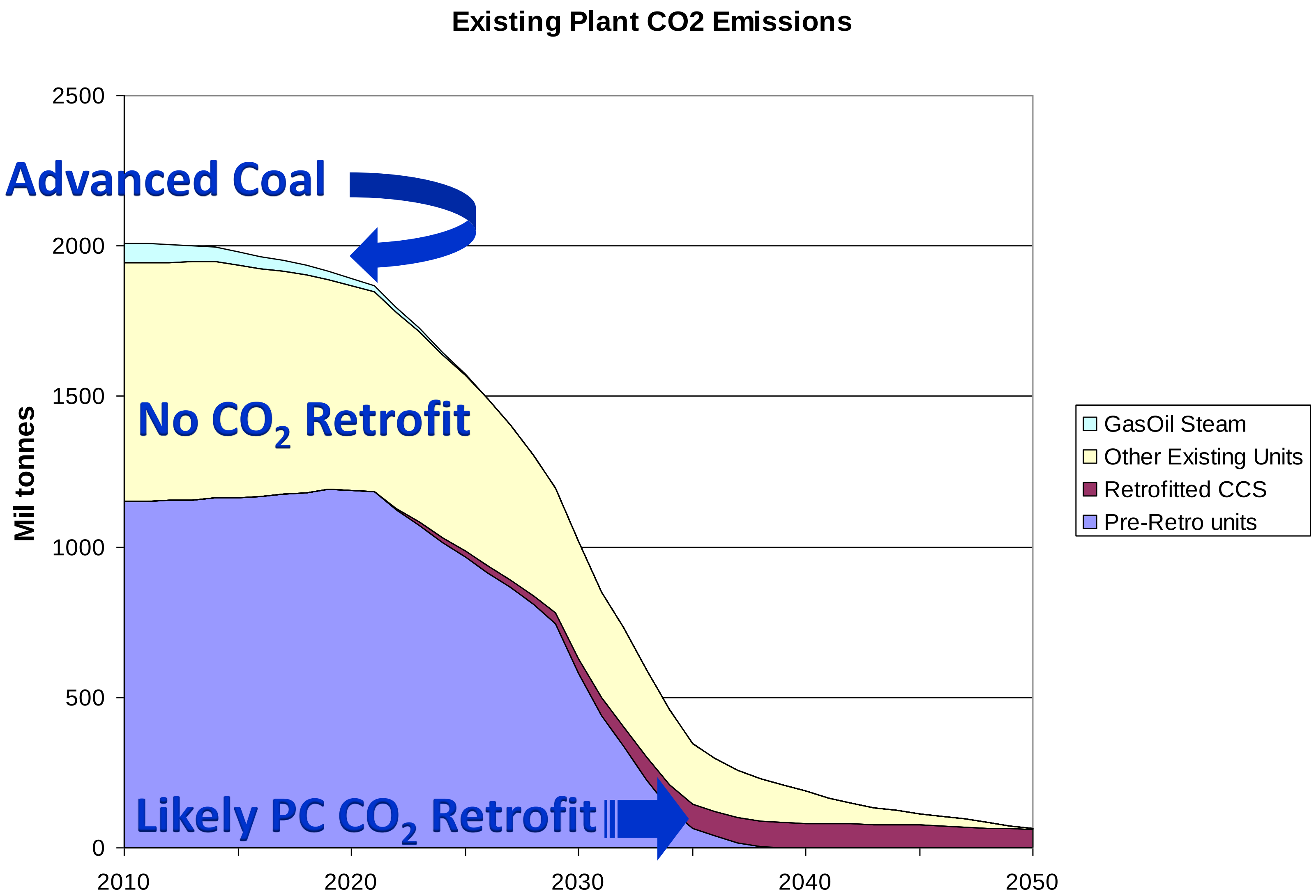
Generation Showing the Conversion of 368 Existing Units to Carbon Capture and Storage and the Penetration of New Advanced Design Oxycombustion and IGCC plants



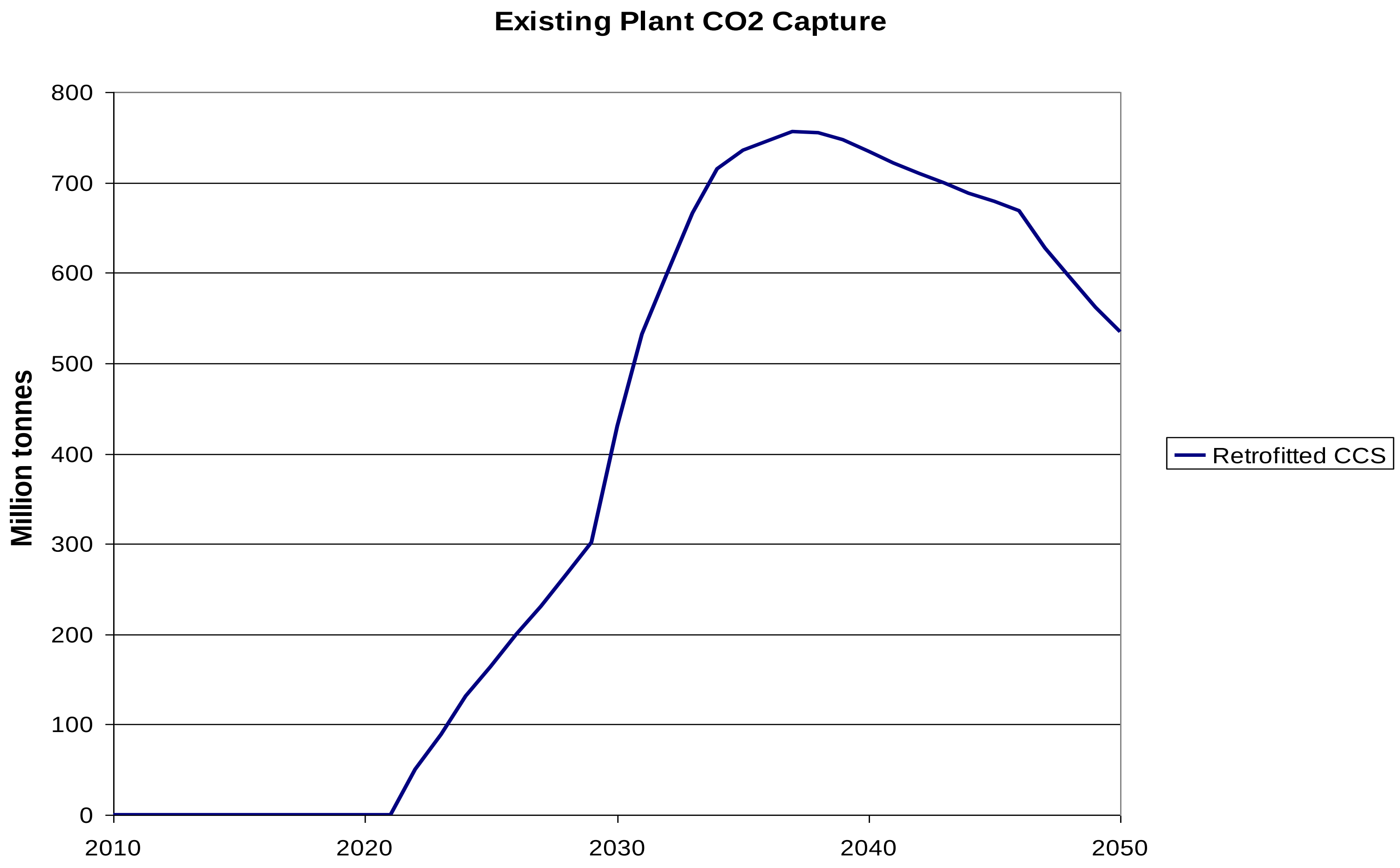
Coal Use May Dip in the 2035 Period



CO2 Emissions from Existing Units Mostly Disappear



CO2 Capture from Existing Units Provides an Opportunity to Gain Experience with CCS Prior to Major Investment in New Advanced Oxyfuel and IGCC Designs



Anticipated Further Work

- Update the AMIGA economic model with the latest thinking on electrification of transportation (plug-in HEVs, high speed rail) and the rapid growth in electrical/electronic equipment, “i.e. Miscellaneous Electrical Loads”, or MELS
- Provide an economic analysis of how the increasing natural gas production will best be used in competing markets for gas (e.g., transportation, CHP)
- Simulate the benefits of retrofitting existing power plants with CCS to meet electrification demands and Energy Security
- Apply selection criteria and cost estimates for ramping up PC unit retrofits with CCS using Phase 2 Enegis data base (as it becomes available)
  - Simulate low carbon capacity expansion using the AMIGA Utility Planning and Compliance model
  - Provide regional system dispatch (how existing units are used in the system)
  - Serve on the Federal/Industry Steering Committee (FISC)
- Participate in the Stanford EMF-24 study, showing the role of retrofitting existing units with CCS.